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SHORT COMMUNICATION

Single leaf area estimation models based on leaf weight of eucalyptus in southern China

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Abstract: Leaf area is an important parameter for modeling tree growth and physiological processes of trees. The single young and mature leaf area estimation models of eucalyptus were developed based on leaf fresh weight. In total, leaf area and leaf weight were measured from 455 fresh leaves of 25 trees of eucalyptus in southern China. The majority of the data (80%) were used for model calibration, and the remaining data (20%) were used for model validation. The linear, compound and power models were tested. Based on goodness of fit, prediction ability and residual performance, we found that linear and power models could best describe the relationship between leaf area and weight for young leaf and mature leaf, respectively. The study provides a simple and reliable method for estimating single-leaf area, which has a good potential in the functional-structural model of eucalyptus.

Keywords: eucalyptus; leaf area; leaf weight; allometric model

Introduction

Leaf area plays an important role in photosynthesis, light interception, water and nutrient use and tree growth, which is also a key determinant of tree productivity (Jose et al. 1997; Bolstad et al. 2000). Therefore, it is a crucial variable in process-based tree-growth models in terms of leaf area index (LAI). Leaf shape, size, density and orientation are essential components of tree architecture (Lourens et al. 2003). Leaf area has been incorporated in recently developed functional-structural models. For example, it is considered as an original organ in the GreenLab functional-structural model (Yan et al. 2004; Letort et al. 2008). In these models, data of leaf area and biomass are required at basic structural unit level (i.e., internode). Although direct leaf area measurement is difficult, some methods can be used to estimate the leaf area, including photocopy-weigh method, ruler method and digital image processing method (Li et al. 2004). Moreover, new instruments such as hand scanner and laser optic apparatus have been invented for leaf area measurements. However, most methods have the limitations such as laborious and time-consuming measurement or requiring expensive equipment and high-level operation techniques. Regression models have been used to estimate leaf area with variables including leaf length, leaf width, fresh and dry weight (Aase 1978; Bhatt et al. 2004; Leroy et al. 2007), which provides a simple and rapid way for leaf area estimation.

Eucalyptus is an important and fast-growing tree species in South China. On one hand, it contributes greatly to Chinese environmental protection and the development of timber industry. On the other hand, it also has some negative impacts. For example, the plantation of eucalyptus requires water more than that of other species, consumes soil fertility very quickly, reduces the biological diversity and so on (Calder 1997; Yu et al. 1999; Huang et al. 2006). A few studies have been carried out on measuring and modeling leaf area of eucalyptus. For example, Xu (2000) detected allometric relationships between tree leaf area and diameter at breast height; Macfarlane (2007) used the fullframe fisheye photography to study the LAI of eucalyptus. However, there are few reports on the allometric relationship between single-leaf area and leaf weight in eucalyptus. Thus, it is necessary to develop an inexpensive, rapid, reliable and easy method to measure leaf area required by foresters. The present study was aimed at providing a method for estimating leaf area of eucalyptus through modeling the relationship between single-leaf area and leaf weight.

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Materials and methods

Experimental site, design and sampling

Data was collected at Huidong County (22°23'−23°30'N, 114°26'−115°38'E), Guangdong Province, P. R. China. The average annual temperature is 22°C and the average annual precipitation is 1 805 mm. The maximum and minimum temperature is 37.3°C and 3.2°C, respectively. The soil is latosol and slightly acidic. Native broad-leaved species mainly include Chinese guger tree (*Schima spp.*), eucalyptus (*Eucalyptus spp.*), camphor (*Cinnamomum camphora*), Taiwan Acacia (*Acacia confuse*) and Castanopsis fissa (*Castanopsis fissa*).

Leaves were randomly selected from healthy eucalyptus (*Eucalyptus grandis ×Eucalyptus urophylla*) trees in December, 2008. A total of 455 leaves were sampled from branches at different orders of 25 trees from 1 to 4 years old, of which 221 were young leaves and 234 were mature leaves. Young leaves were mainly located on the top of branch and their color was light. In contrast, mature leaves were mainly in the stem or the middle and base of branch, and their color was dark. Mature leaves had stopped expanding. All the leaves were weighed on the site with an electronic balance with a precision of 0.01g. After the leaves were taken to the laboratory, a scanner was used to transform the leaves to the images, and digitalize them to attain the leaf area with the help of MapInfo software. Table 1 shows the statistical summary on sampled leaves.

Table 1. Statistical summary of sampled leaves

Statistics	Mature leaves		Young leaves	
	Area (cm^2)	Weight (g)	Area (cm^2)	Weight (g)
Mean	29.57	0.51	13.45	0.28
Max	62.00	1.19	45.82	0.97
Min	6.83	0.11	1.15	0.03
Std	9.98	0.20	10.52	0.22

Model calibration and validation

Since there were significant differences in fresh weight between young and mature leaves (Table 1), the models between leaf area and leaf weight were developed for these two kinds of leaves, separately. The scatter diagram shows that the relationship between leaf area and leaf weight was quite linear (Fig. 1). Therefore, the linear, power and compound models were selected to fit the data to determine the best one through the least-square estimation.

$$y=a+bx \quad (1)$$
$$y=a(b^x) \quad (2)$$
$$y=a(x^b) \quad (3)$$

where, x is the leaf fresh weight, y the leaf area, and a and b are parameters.

Besides the significance of estimated parameters, the models were evaluated by prediction errors and precision (Table 2). The parameters included total relative error (E_1), average relative error (E_2), average absolute relative error (E_3), root mean square error (E_4), and predicted precision (P). All data was randomly split into two parts, the data of 80% were used for model calibration and the remaining 20% for model validation.

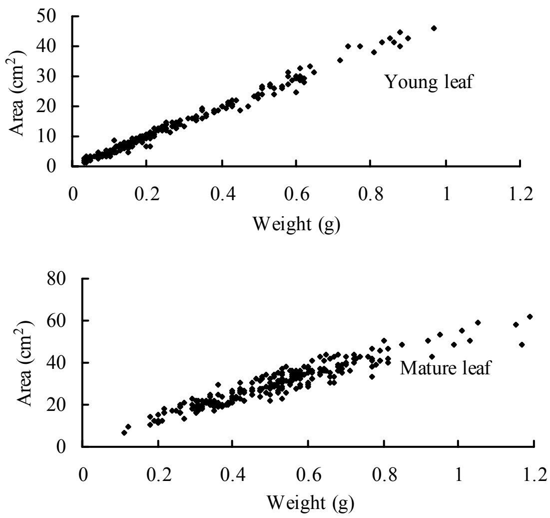


Fig. 1 Relationship between leaf area and weight

Table 2. Statistics on prediction error and precision

Symbol	Formula	Ideal value
E_1	$\dfrac{\sum_{i=1}^{n} o_i - \sum_{i=1}^{n} e_i}{\sum_{i=1}^{n} e_i} \times 100\ \%$	0
E_2	$\dfrac{1}{n}\sum_{i=1}^{n} \dfrac{o_i - e_i}{e_i} \times 100\ \%$	0
E_3	$\dfrac{1}{n}\sum_{i=1}^{n} \dfrac{\lvert(o_i - e_i)\rvert}{e_i} \times 100\ \%$	0
E_4	$\sqrt{\sum_{i=1}^{n} \dfrac{(o_i - e_i)^2}{n-k}}$	0
P	$1 - \dfrac{t_{1-\alpha} \cdot \sqrt{\sum_{i=1}^{n} (o_i - e_i)^2}}{\bar{e} \cdot \sqrt{n(n-k)}} \times 100\ \%$	1

Notes: o_i, e_i, n, $\bar{e}$, k and P are the measured value, predicted value, sample size, average predicted value, the number of model parameters, and prediction precision, respectively. The t_α is T value with the confidence level, and α is 0.05 in the study.

Results and analysis

All the regression coefficients are significant at $p < 0.05$ (Table 3). The values of R^2 were generally high and acceptable for all the models. For mature leaves, model 3 had the highest R^2 (0.924), followed by model 1 (0.905) and model 2 (0.823). For young leaves, model 1 had the highest R^2 (0.988), followed by model 3 (0.971) and model 2 (0.825). For mature leaves, model

3 had a good performance in error statistics except E_1, which was also very small (0.328%) (Table 4). However, for young leaves, model 1 performed well except for E_3, which was very close to that of model 3. Both young and mature leaves had high *P* values. Almost all the models were above 95% (except model 2 (90.576%) for young leaves).

Table 3. Regression models between the leaf area and leaf weight for mature and young leaves

Models	*a*	*b*	*F* (p=0.05)	R^2
		Mature leaves		
$y=a+bx$	4.453 (0.652)	48.526(1.162)	1743	0.905
$y=a(b^x)$	11.765(0.376)	5.302(1.302)	857.736	0.823
$y=a(x^b)$	53.299(0.631)	0.891(0.019)	2246	0.924
		Young leaves		
$y=a+bx$	-0.004(0.142)	48.632(0.414)	1.3790	0.988
$y=a(b^x)$	3.423(0.148)	37.064(4.677)	819.790	0.825
$y=a(x^b)$	47.456(1.190)	0.988(0.013)	5742	0.971

Note: Standard errors are shown in the brackets.

Table 4. Statistics of three models for mature leaves and young leaves

Model	E_1 (%)	E_2 (%)	E_3 (%)	E_4	*P* (%)
		Mature leaves			
$y=a+bx$	0.002	-0.490	8.207	3.048	98.660
$y=a(b^x)$	0.123	1.055	10.697	5.214	97.704
$y=a(x^b)$	0.328	0.483	7.625	3.004	98.674
		Young leaves			
$y=a+bx$	0.003	0.856	10.691	1.221	98.690
$y=a(b^x)$	-6.135	6.308	29.515	9.362	90.576
$y=a(x^b)$	-1.196	1.170	10.682	1.259	98.634

Good models should have no significant heterogeneous residual variance. Fig. 2 shows that the residual values of mature leaves mainly varied from -5 to 5, -20 to 10, and -5 to 5 for models 1, 2 and 3, respectively. For young leaves, the residual values mainly varied from -2 to 2, -20 to 10, and -2 to 2 for models 1, 2 and 3, respectively (Fig. 3). Heterogeneous residual variance was observed for model 2 of both young and mature leaves. Errors of models 1 and 3 were randomly scattered, and the residual variance was homogeneous. The distributions of residuals of model 1 and model 3 were more desirable.

Based on the above analyses, we selected model 1 and model 3 as the best models for estimating young and mature leaf area, respectively. For model validation, an independent data set was used to assess the predictive power of the selected models. In Table 5, the statistics of young-leaf models were better than those of mature leaves. For young leaves, the total relative error and the average relative error were both less than 5%. The average absolute relative error was less than 10%. For mature leaves, the total relative error and the average relative error were both less than 10%, and the average absolute relative error was less than 15%. Their root-mean-square errors (RMSE) were 0.866 and 3.937, respectively. The predicted precisions were both above 95%.

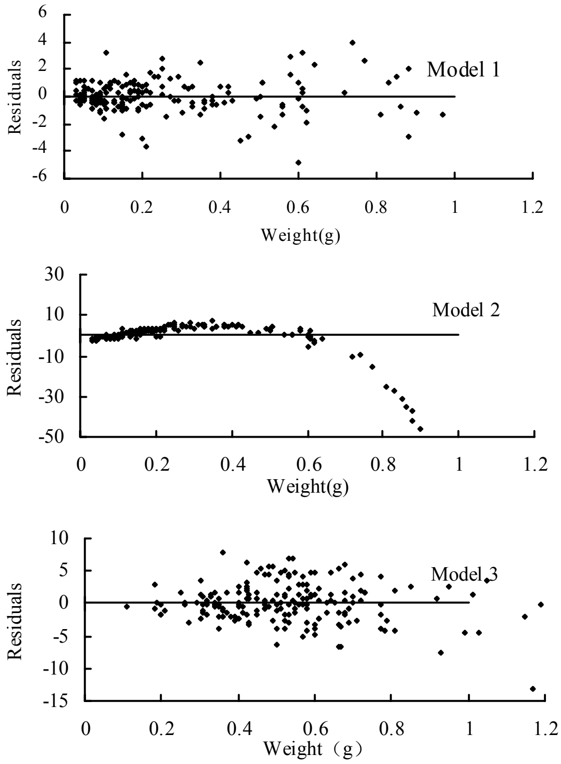


Fig. 2 The residual distribution of models for mature leaves

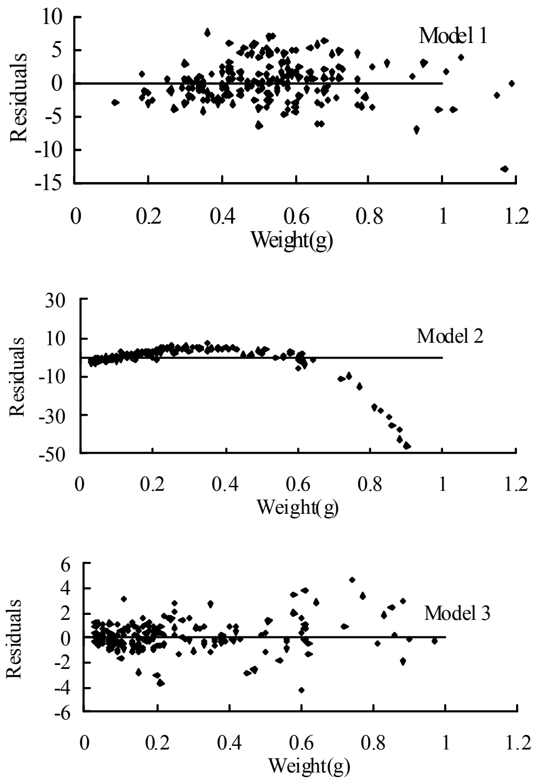


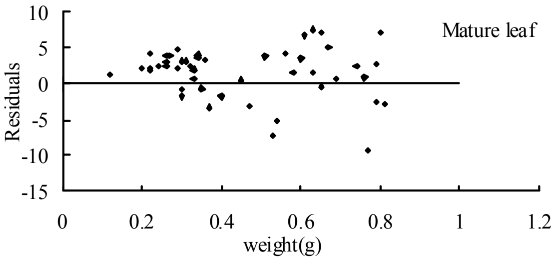
Fig. 3 The residuals distribution of models for young leaves

Fig. 4 shows the residual distribution obtained from the validation data set, where residuals were randomly scattered. Most of residuals fallen between -5 and 5 for mature leaves,

whereas the residual values mainly varied from -1 to 2 for young leaves. They were mostly less than their respective standard deviation. So we can conclude that there is a high mutual independence between residual and dependent variable. So model 1 and 3 are statistically reliable for estimating leaf area from fresh leaf weight.

Table 5. Validation results of regression models between leaf area and leaf weight

Leaf type	E_1 (%)	E_2 (%)	E_3 (%)	E_4	P (%)
Mature leaf	6.154	8.102	13.452	3.937	97.152
Young leaf	1.766	2.834	5.460	0.866	98.644



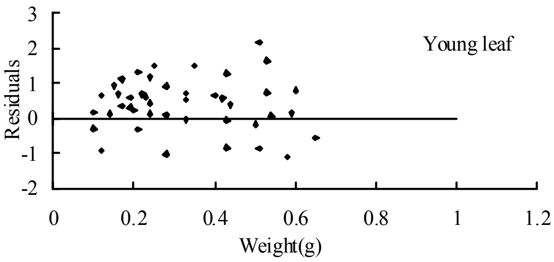


Fig. 4 Residual distribution of final models for estimating leaf area from leaf weight

Conclusions and discussion

In this study, we developed some models to estimate single leaf area from leaf weight for eucalyptus. Model validation showed that these models provided reliable estimation with high precision. From associated fresh weight, the mature-leaf area and young-leaf area could be accurately estimated by power model (y=53.299($x^{0.891}$)) and linear model (y=-0.004+48.632x), respectively. Similar allometric relationships have been commonly observed between leaf area and leaf length, leaf width in most literatures (Awal et al. 2004; Leroy et al. 2007). Since biomass has to be measured at organ or structural unit level in functional-structural models, the models we presented are potentially useful for functional-structural modeling of eucalyptus. However, the relationship between leaf area and weight changes with biotic and abiotic variables such as season factors, position in tree, leave ages and climate factors, etc. Further study of the effects of these factors on the relationship is needed in future.

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